Caribbean Disaster Mitigation Project
Implemented by the Organization of American States
Unit of Sustainable Development and Environment
for the USAID Office of Foreign Disaster Assistance and the Caribbean Regional Program

Natural Hazards Vulnerability of the Dominica Hydroelectric Expansion Project

TABLE OF CONTENTS

Introduction
Hydroelectric Components
Natural Hazards
Dominica Hydroelectric Expansion
Reducing Vulnerability
Discussion
References
Figures Appendix A: Detailed Description of Project Components
Appendix B: Recommended Maintenance Procedures

INTRODUCTION

One of the current projects of the Caribbean Disaster Mitigation Project, established by the Organization of American States, is to assist the Caribbean Electric Utility Services Corporation (CAULEC) in reducing losses from natural hazards. To see the value of this effort, one need only look at recent examples of electrical Systems impaired by natural hazards. An example is the effect on St. Vincent by the September 8, 1986 passage of Tropical Storm Danielle. This storm event triggered landslides which swept away a considerable length of pipelines conveying water to hydroelectric stations. The generating capacity of both the South Rivers power station in the northeast part of St. Vincent and the Richmond power station in the northwest were affected. Altogether, the landslide activity reduced generating capacity of the island by 36 percent. This reduction had to be endured until the woodstave pipelines could be repaired some time later.

The initial collaboration between the Caribbean Disaster Mitigation Project and CARILEC is a pilot vulnerability audit of the St. Lucia Electrical Utility (LUCELEC). To provide a complete examination of natural hazard vulnerability, this audit needed to include a hydroelectric facility. Because none are currently operational on St. Lucia, it was arranged to use the recent hydroelectric expansion project on Dominica operated by the Dominica Electric Services Limited (DOMLEC).

This report documents the findings from the vulnerability to natural hazards audit of the hydroelectric expansion project. The audit included examining actions necessary to reduce vulnerability through both retrofitting and maintenance. This information will be used to establish related costs for reducing vulnerability.

Information used in the preparation of this report was gathered from several sources during Nov. 28 to Dec. 2, 1994. Three documents prepared for the Dominica Hydroelectric Expansion Project were reviewed: the 1984 feasibility study, the 1987 design criteria report, and an undated project completion report. Interviews with Mr. F. Adler Hamlet, Engineering Manager, Dominica Electric Services Limited (DOMLEC) supplied additional valuable information. Mr. Charles McClean, DOMLEC, was most helpful during a field review of the components of the Dominica Hydroelectric Expansion Project. Documents prepared in 1987 for the Organization of American States and the Government of the Commonwealth of Dominica on landslide hazards and papers on natural hazards on Dominica published in scientific literature were also consulted in the preparation of this report.

HYDROELECTRIC COMPONENTS

Hydroelectric facilities are composed of several different components. These include: 1) the power station, 2) water conveyance and control structures, and 3) impoundments. Theses components are combined to ensure the delivery of water at the most favorable head for generating electricity.

Power stations consist of one or more buildings which house the turbines which generate electricity, their operational mechanisms, and control facilities. Another major component is the switchyard. This facility which is generally located near the power station includes transformers for changing the voltage for transmission though the power grid and connecting cables to the transmission system.

Water conveyance and control structures include both pipelines and tanks. Water used to generate hydroelectric power is usually collected at one point and taken to the power station which is located some distance away. This necessitates pipelines of various types to effectively convey the water. Tanks are typically used to ensure a constant head on the water entering the power station. Both surge tanks and balancing tanks are used for this purpose.

Impoundments ensure an adequate amount of water is available to generate the electricity at the power station. Reservoirs are the most common form of impoundment. Impoundments are created by placing a dam or dikes at narrow locations along river valleys. This permits water to pool behind these structures. Location of dams take advantage of both a position where a small structure will create an impoundment and topographic conditions which permit adequate storage area for the impounded water. The shoreline of the reservoir is an element of the reservoir impoundment. Other impoundments used in hydroelectric facilities include diversions and intakes. Diversions are small structures which interrupt the natural flow of a stream to permit water to be directed into a pipeline. Intake structures may be part of diversions. Intakes are placed to prevent sediment from entering the pipeline and reaching the turbines at the power station.

While roads are not a component only found at hydroelectric facilities, they should not be forgotten in assessing vulnerability of the facilities. Roads are needed to transport workers to and from the power stations and switchyard, They also provide access for maintenance of reservoirs, pipelines, and diversions.

NATURAL HAZARDS

Hydroelectric facilities are vulnerable to several types of natural hazards. This vulnerability is a consequence of the factors necessary to generate hydroelectric power. One factor is the nature of hydroelectric power generation. It involves buildings and other civil works which will be vulnerable to nature hazards unless their design is resistant to the effects of these hazards. Another factor are the unique components of hydroelectric facilities: pipelines, transmission lines, impoundments, and water control structures. The third component is the nature of the landscape where hydroelectric generation is sited. It must involve a significant drop in elevation over a relatively short distance. This means hydroelectric generation occurs in steep, mountainous terrain with significant precipitation seasonally or annually. The same physical conditions which favor hydroelectric generation also favor a host of geologic hazards.

Landslides are one of the most pervasive natural hazards. This hazard affects hydroelectric facilities in several ways. Landslide movement can remove support to the foundations of power stations, switchyards, dams, and other structures. It can also affect the function of these facilities by impact or burial from locations upslope. Landslides deliver large amounts of sediment to streams and rivers. This sediment can exceed the ability of intakes to prevent its entry into pipeline and cause damage to turbines. Over time, sediment from landslides can affect the efficiency of diversions and reduce the storage capacity of reservoirs.

Flooding is another type of hazard to which hydroelectric facilities are vulnerable. The location of power stations and switchyards may be within areas subject to periodic flooding. This impairs or prevents their operation during times of flooding. Flooding also influences the operation of reservoirs to the extent that delivery of water to the power station may be hampered by actions required to protect the integrity of the reservoir. While flooding is typically a consequence of intense rainfall, it may also result from failure of landslide dams which have created temporary impoundments.

Wind is another natural hazard. It is mainly a problem to the power station and switchyard facilities. The buildings housing the power generating facilities must be able to withstand expected winds. This is also true for the connecting cables from the switchyard to the transmission grid. High winds are associated with major storm fronts such as hurricanes.

Earthquakes may affect hydroelectric facilities in two ways. First, ground shaking can cause displacement, foundation failure, and structure damage to facilities. This can range from cracks in the wall to failure of the dam forming the reservoir. Second, earthquakes may result in rupture at the ground surface along the fault line. Rupture may involve either vertical or horizontal displacement or both. Structures located across a surface rupture area will be stressed and commonly torn apart by this action along the fault line.

Volcanic eruption can affect hydroelectric facilities at some distance from the eruptive center. Lava flows from the volcano that reach hydroelectric facilities will cause damage from both the heat radiated from the flows and from burial of the structures. Volcanic ash ejected into the air may fall at the hydroelectric facility. This raises the possibility of fine, abrasive material entering pipelines and damaging turbine blades, short circuiting lines in switchyard, and impacting control mechanisms at the power station. The ash will also cause damage to any internal combustion engines used at the facilities for auxiliary purposes unless their air intakes are protected and lubrication is done on a frequent basis.

DOMINICA HYDROELECTRIC EXPANSION

Description of Project Components

The Dominica Hydroelectric Expansion Project comprises the Roseau river valley from Fresh Water Lake to the capital city of Roseau. The expansion involved two schemes to increase hydroelectrical generating capacity above the capacity of the existing Trafalgar and Padu power stations (Fig. 1). A feasibility study was begun in 1983 for this expansion. Final design was completed in April 1987 and construction commenced in January 1989. The Laudat power station was put in service in December 1990 and the New Trafalgar power station was commissioned in September 1991.

The Laudat scheme develops 211 m of head between Fresh Water lake and the village of Laudat. It includes the following components:

1. concrete weir **-** this weir on the Clarke's river diverts flow into a 450 mm dia. woodstave pipeline. The pipeline discharges into the head of the Three Streams canal which collects the discharge of three small mountain streams before flowing into Fresh Water Lake.
2. rockfill dam **-** this 10-m high dam raised the level of Fresh Water lake to create a reservoir with a live storage capacity of 500,000 m3 (Fig. 2).
3. pipeline and surge tank **-** water is conveyed from Fresh Water Lake around the side of Morne Macaque in a 914 mm dia. woodstave pipeline to a woodstave surge tank (Fig. 3).
4. pipeline - to convey water from the surge tank to the power station, a 760 mm dia. steel pipeline is used (Fig. 4).
5. power station **-** the powerhouse is a building which contains a single 1300 kw horizontal axis Pelton turbine and associated control works (Fig. 5).
6. switchyard **-** adjacent to the powerhouse is a switchyard with a transformer to step up the voltage from 2.2kV to 11kV and feed the power via a short length of overhead cable to connect to the existing transmission network.

The New Trafalgar scheme develops 283 m of head between the tailrace of the Laudat power station and the village of Trafalgar at the foot of Trafalgar Falls. It includes the following components:

1. diversion weir and intake **-** a concrete diversion weir at the outlet of Titot Gorge on the Roseau river diverts flow into an intake with a sediment removal tank before entering a pipeline (Fig. 6).
2. pipeline **-** a 1016 mm dia. woodstave pipeline conveys water from the Titot Gorge diversion to the Trafalgar Balancing tank.
3. diversion weir and intake **-** another concrete diversion weir is on the stream adjacent to the Laudat power station

and diverts flow into an intake with a sediment removal tank before entering a pipeline.

4. pipeline - a 760 mm dia. woodstave pipeline conveys water from the Laudat tailrace to the Trafalgar Balancing tank.
5. balancing tank - the Trafalgar balancing tank has a gross storage volume of 5,500 m3 and is found at the power intake structure for the New Trafalgar power station.
6. pipelines - a 1016 nun dia. pipeline comprised of both woodstave and steel sections conveys water from the balancing tank to the top of Trafalgar cliff. There a 914 mm dia. steel pipeline passes the water down the Trafalgar cliff and feeds into both the existing and new Trafalgar power stations (Fig. 7).
7. power station - the New Trafalgar power station contains two 1700 kw horizontal axis Pelton turbines with associated switchgear. The building housing these facilities also houses a control room (Fig. 8).
8. control tank - a concrete control tank combines flows from both Trafalgar poser stations with the existing Padu diversion intake for conveyance to the existing Padu power station.
9. switchyard - adjacent to the New Trafalgar power station is a switchyard with two transformers to step up the voltage from 2.2 kV to 11 kV and a short length of overhead cable connecting it to the existing transmission network (Fig. 9).

In summary, the Dominica hydroelectric expansion project includes two power stations and two switchyards, four tanks, 6 pipelines, three weir/intakes, and one dam. These structures represent all the major components typically found at a hydroelectric facility. These facilities are dependant for access on several roads including the road to Fresh Water Lake. Detailed descriptions of these components are contained in Appendix A.

Design Criteria for Natural Hazards

The following sections describe the design criteria proposed by consultants for the Dominica Hydroelectric Expansion Project (Anonymous, 1984, Anonymous, 1987). The later section entitled **Vulnerability to Natural Hazards** gives specific information on how this design criteria were employed in construction of the Dominica Hydroelectric Expansion Project and its post-construction performance. Some specific deficiencies and inconsistencies in the criteria proposed for this project are noted.

Landslide Hazard - The slope stability design criteria specified for this project was limited to constructed embankments and foundations. Analysis was done using the modified Bishop's Method for circular failures. Various loads were analyzed to determine the Factor of Safety (FOS) which was considered the minimum value. Analysis for design criteria was applied to different types of structures contemplated for the Dominica Hydroelectric Expansion Project.

The Factor of Safety is 1.0 at the point when failure would occur. A value higher than 1.0 is necessary to avoid failure. In general practice, an FOS of 1.5 is acceptable as a minimum when there is little uncertainty in the data used for analysis and low potential loss of life or property. When there is uncertainty in the analyzed data or high potential loss of life or property, an FOS of 2.0 is considered more appropriate (Duncan and Buchigni, 1975).

Fresh Water Lake Dam - this analysis used material property values assigned to various materials used in construction of the dam. Different load conditions which the dam might be subjected to during its design life were analyzed to determine the minimum FOS that would be expected. Table 1 displays these minimum values for these different loads. It shows that a 0.1 g horizontal seismic load at the end of construction and a 0.1 g horizontal acceleration while steady seepage with full supply level would both be conditions bringing the dam to near failure.

Table 1. Minimum FOS for Different Load Conditions at Fresh Water Lake Dam

Loading Condition	Factor of Safety*
end of construction	1.3
steady seepage with full supply level	1.5
end of construction with 0.1 g horizontal acceleration seismic loading	1.05
steady seepage with full supply level and 0.1 g horizontal acceleration seismic loading	1.1

* Minimum

Diversion weir/spillway - A similar slope stability analysis was done for these structures. The load conditions were defined normal, unusual, and extreme conditions representing different combinations of conditions which might be experienced by the structures during their design life. Table 2 displays the minimum FOS established for these structures.

Slope stability analysis for intakes, inlet channels and tanks addressed a number of circumstances which might be expected during the design life of these structures. The slope stability analysis grouped these situations into two groups; normal and extreme loading. The following describes the situations represented by these two groups:

a) normal loading - 1) dead load, 2) earth pressure, 3) load from water level experienced during normal operating conditions, 4) surcharge load, and 5) uplift,

b) extreme loading - Case I - dead load, earth pressure, load from water level experience during 100yr flood, uplift, and surcharge, Case II- normal loading with 0.1 g horizontal acceleration, Case m - dead load, earth pressure with tank empty, and with surcharge load from construction equipment.

Table 2. Minimum FOS for Different Loads on Diversion Weir/Spillway

Loading Conditions	Factor of Safety*
Normal - upstream water at crest elevation, no tail water, normal uplift assuming 50 % drainage efficiency and sediment level with crest	2.0
Unusual - upstream water level at design flood (100 yr for weirs, 1000 yr for Fresh Water Lake dam spillway, tail water 0.3 m above sill of downstream apron, and sediment level with crest	1.5
Extreme - both normal conditions with 0.1 g horizontal acceleration and unusual conditions with full uplift (drainage under downstream apron ineffective)	1.25

* Minimum

The stability analysis performed by the consultants established the minimum FOS values for intakes, inlet channels, and tanks displayed in Table 3.

Table 3. Minimum FOS for Intakes, Inlet channels, and Tanks.

Loading Conditions	Factor of Safety*
Normal loading	2.0
extreme loading	1.25

*Minimum. NOTE: the design table included an FOS of 1.5 for unusual conditions for intakes and tanks but did not specify what the specific conditions were which would define unusual conditions.

Despite the information on landslide hazard which is documented in a report (DeGraff, 1987) and the availability of landslide hazard maps for Dominica, no design criteria was established for natural slope stability. Nor was there any design criteria specified for dealing with natural instability of slopes despite geotechnical studies carried out under the feasibility study for the diversions, dam, and pipeline locations. A design criteria for natural slope instability might be to design to a higher minimum Factor of Safety for cutslopes in areas of moderate landslide hazard. For example, an FOS of 2.0 might be appropriate. A design criteria for natural slope stability which might threaten the location of specific structures could be to require an engineering geologic assessment of the slopes above that structure.

Flood hazard- Flood criteria was established for both weirs and the Fresh Water Lake dam. Weirs on Clarke's river and Titot Gorge were required to pass the 100 year flood event discharge (1 percent probability of occurrence) at 1 m surcharge over the river crest. This amounted to discharges of 30.2 m3/sec and 25.5 m3/sec, respectively. For Fresh Water Lake dam, the spillway was required to pass 15.87 m3/sec discharge for the 1000 year flood event with 1.58 m surcharge over normal full supply level and 10.79 m3lsec discharge for the 100 year flood event with 1.22 m surcharge over normal full supply level.

No criteria was found in the consultant report which addressed flood hazard for other structures such as the power station or switchyards.

Wind Hazard - Structures are required to withstand loads calculated in accordance with the National Building Code of Canada and based on a 54 m/sec velocity. This velocity represents the 3 sec. gust speed having a 1 in 50 year return period. The consultants provided no references or other information on how this criteria was established as appropriate for this project.

Seismic Hazard - Earthquake loads were based on Zone 3 described in the National Building Code of Canada (1980). The report prepared by the consultants provided not references or other information on the specifics for Zone 3. It is unclear what aspect of seismic hazard is addressed by this design criteria. It is assumed this criteria addresses the effect of ground shaking. The design parameter used in this assessment was stated to address "...hydrodynamic pressures resulting from the horizontal ground acceleration (0.1 g) determined on the basis of the Westergaard Curve modified by Zangar in USBR Monograph 11." (Anonymous, 1987).

Slope stability analyses described earlier also included seismic load effect in some cases. The ground acceleration was stated to be that associated with 0.1 g horizontal acceleration.

The effect of fault rupture was not mentioned nor was a criteria or evaluation recommended.

Volcanic Hazard - No mention was made of a possible volcanic hazard or criteria for design to resist the effects of ash fall in the consultant reports..

Vulnerability to Natural Hazards

Landslides - Landslides are a common natural hazard on Dominica. DeGraff and others (1989) noted that nearly 2 percent of the land area on Dominica is disturbed by past or existing landslides. More than 980 landslides were mapped during an inventory conducted in 1987. From this mapping, it was found that the average landslide was about 4 hectares in size. The largest landslide mapped at that time was 12.5 hectares (DeGraff, 1987). Dominica has roughly 1.2 landslides per square kilometer. While rockfalls and rockslides are recognized within this landslide population, the most common landslide type are debris flows. These are shallow failures occurring at depths of several meters (DeGraff and others, 1989, Walsh, 1985).

Landslides have already affected the Dominica Hydroelectric Expansion Project (Anonymous, undated). During construction, natural slope instability either delayed construction work or required changes in original designs at three locations (Fig. 10). The first location was the Clarke's river diversion. Pipeline excavation commenced at the end of April 1989. In May, the contractor stopped work because progress was hampered by occasional landslides and wet conditions. Further examination was made of slope conditions to assure that slopes would remain stable following excavation. Work recommenced in July.

Landslides affected another part of the project in 1989. Excavation of the pipeline right-of-way between Fresh Water Lake and the surge tank above the Laudat power station was done between June 1989 and September 1989. However, a large landslide occurred at the end of August 1989 during a heavy storm (Fig. 11). This landslide from the slopes of Morne Macaque destroyed part of the pipeline pad. The subsequent passing of hurricane Hugo the following month and several other several storms in the succeeding months caused additional damage to the pad and destroyed the site access road (Fig. 12). A design change was required to complete the pipeline along its original alignment. This was accomplished by erecting a modular bridge across the slide path to support the pipeline and restore vehicular access to Fresh Water Lake. Completion of the pipeline was delayed until October 6, 1990 due to the time required to purchase materials and subsequent construction of the bridge. This design change imposed an additional cost of about $480,000 EC on the project.

Natural slope instability also caused a design change in 1990 (Anonymous, undated). The Contractor responsible for installing the pipeline down the face of Trafalgar cliff employed a subcontractor with experience in acrobatic services to install an overhead cableway for dismantling the existing pipe and completing construction of the new pipeline. In April, rock movement was suspected during excavation of the recess in the cliff face for the new pipeline. This necessitated removal of a rock overhang and installation of an anchoring program. Completion of the anchoring program was delayed by lack of materials and breakdown of equipment. When work on the excavation resumed in September 1990, but stopped later the same month when a section of rock along the recess slipped. This resulted in installation of another anchoring program and a design change in the lower portion of the pipeline support from platforms to a concrete encasement (Fig. 13). The cost to the project for the change in design to support the pipeline is estimated to be $563,000 EC.

The area affected by the Dominica Hydroelectric Expansion Project is mapped on the landslide hazard map produced in 1987 as having areas with moderate and high landslide hazard (DeGraff, 1987). The three locations where construction problems due to landslides or natural instability occurred are all within areas mapped as high landslide hazard. This level of hazard should have initiated a more intensive, site-specific assessment of natural slope stability by engineering geologists to ensure appropriate design criteria identified.

Location of the pipelines in high hazard areas without adequate consideration of this hazard in the design also has caused higher operational costs for the DOMI£C (Mr. F.~ Hamlet, 1994, Pers. Comm.). In May 1992, two landslides occurred along the Clarke's river diversion pipeline. Both landslides broke the pipeline and caused temporary loss of water to the Fresh Water Lake. One slide occurred near the Clarke's river diversion. It displaced the pipeline and partially buried it (Fig. 14). It took about 3 weeks for hand crews to remove the debris and repair the pipeline. The site was inaccessible to equipment to assist in this task. The second landslide occurred along the pipeline just south of the throughcut area. This slide displaced the pipeline laterally to cause the break. This material was also removed by hand crew during pipeline repair. Both failures were in soil with movement occurring at a shallow depth estimated to be within 1 to 4 meters. The landslide near the diversion structure included several large boulders with diameters of 0.5 to 1.5 meters. The restoration of the pipeline to service after the May 1992 landslides was estimated to be $70,000 EC.

In April 1993, two more landslide impacted water delivered to and from Fresh Water Lake. One landslide occurred at nearly the same location on the Clarke's river pipeline south of the throughcut as the one in May 1992 (Figs. 15 and 16). The other landslide occurred on the pipeline from Fresh Water Lake to Laudat power station. It was located just below the dam at Fresh Water Lake. Repair to these pipeline breaks required the same type of work as done the previous year. The cost is estimated to be about $30,000 EC. Neither repair cost includes lost revenue related to power generation.

Earthquakes **-** The design criteria for ground shaking from an earthquake took into account the tectonic earthquake record for Dominica and surrounding region. As described in Anonymous (1984), earthquake hypocenters are at 50 to 125 kilometers under Dominica and at 10 to 30 kilometers further east. A 76-year instrumental record (1885-1981) was taken for the area south of Antigua to Trinidad as the basis for seismic design. The statistical treatment carried out on this record produced a Design Basis Earthquake of 0.1 g with a recurrence interval of 1 in 100 years. This analysis used a conservative hypocentral distance of 69 km based on the most unfavorable combination of epicentral distance (47 km) and reported focal depth (50 km). Ground motion at the site was estimated using the attenuation curves proposed by Schnabel and Seed (1973). The Design Basis Earthquake of magnitude 7.25 determined from the record and hypocentral distance of 69 km yield the peak horizontal acceleration in rock of 0.1 g. The lesser magnitude of past recorded earthquakes suggested that 0.05 g was the acceleration more commonly achieved. The most destructive earthquake on Dominica in historic times was the 1843 earthquake to which the consultants attributed a peak acceleration of less than 0.15 g. This comparison formed the rationale for selecting 0.1 g acceleration as an appropriate level for project design.

A design criteria for ground shaking is needed for both buildings and other structures associated with a hydroelectric facility. I must be based on a reasonable interpretation of expected earthquake occurrence at the project and appropriate ground acceleration value. The value of 0.1g used by the consultants for the Dominica Hydroelectric Expansion Project may not be appropriate (T. Gibbs, 1995, written comm.). Published acceleration values by Dr. John Shepard of the University of West Indies (St. Augustine) and on nearby St. Lucia (Aspinail and others, 1994) would suggest an acceleration of 0.3 g might be more appropriate. This clearly shows the importance of using regional and local data and experience in developing seismic design criteria for hydroelectric projects. It is unclear whether the seismic design criteria as implemented to satisfy the National Building Code of Canada design requirements is fully adequate. There is real uncertainty when seismic design requirements for one area are applied to another area where underlying assumptions and data concerning seismic effects may differ. The ground acceleration criteria of 0.1 g was applied to the slope stability and foundation stability for the Fresh Water Lake dam, the weirs, tanks, and channel inlets. It is not apparent from the documents whether this design criteria was applie4 to pipeline design. While it may not be possible or cost-effective to make a pipeline resistant to expected ground motion, knowing the likelihood of this effect will establish whether cut-off valves to prevent water loss following rupture would be prudent to include in the design.

No design criteria was provided for fault rupture. There is little which can be done to prevent displacement or rupture of a fault from damaging or destroying a structure. A common practice is to establish a setback distance from an identified fault capable of rupture to avoid such a loss. The lack of geologic mapping identifying any faults makes it uncertain as to the likelihood of fault rupture hazard to components of the Dominica Hydroelectric Expansion Project. If faults with the capability for rupture cross pipelines or pass under structures, the potential for fault rupture damage would exist.

Floods - The flood criteria for the Dominica Hydroelectric Expansion Project used by the consultants was based on flood studies and measurements carried out on Martinique. This was necessary due to the absence of such records on Dominica. It was judged an adequate approach because the records from Martinique were from the central Piton region which is the wettest part of that island and differences in elevation between the Piton region in Martinique and the Fresh Water Lake region in Dominica would be unlikely to be affect the severe floods of 20 year return period or more which are typically related to hurricane or frontal weather systems. The Martinique flood studies were summarized into a generalized flood magnitude-frequency-drainage area curve. The drainage area above the Clarke's river diversion and above the Titot Gorge intake were compared to the curve to determine the flood magnitude for 10, 20, 50, and 100 year return periods.

It was noted in the Feasibility Study (1984) that this approach to estimating flood magnitude on Dominica should not be used to extrapolate beyond a return period of 100 years. However, the design criteria report (1987) specified two flood criteria for the spillway at Fresh Water Lake; one for a 100 year return period and one for a 1000 year return period. The latter design criteria would seem to be unnecessary and lack scientific credibility.

Wind - The design criteria for wind hazard was a basic velocity of 54 m/sec. This was specified as the 3 second gust speed with a 1 in 50 year return period: It is understood that this criteria is based on a study carried out by the Boundary Layer Wind tunnel Laboratory at the University of Western Ontario for the Pan-Caribbean Disaster Preparedness Project and is what would be expected at a 10-meter height in an open environment Cr. Gibbs, 1995, Written Comm.). This seems to be a well-established criteria appropriate to the project area.

Volcanic - While no design criteria was specified for volcanic hazards, the feasibility study (1984) did address the nature of volcanism on Dominica. It was noted that Dominica is volcanically active with some volcanic activity occurring in the present-day in the form of hot springs, fumaroles, and a boiling lake. The most recent recorded eruption was a steam eruption in 1880 in either the vicinity of the Boiling Lake or the Morne Patate area. Otherwise, volcanic activity is presently manifested as swarms of earth tremors at shallow depth (near surface to 10 km). Swarms of earthquakes are reported for 1841, 1893, and 1937-38. Swarms are recorded for 1974, 1976, and 1982. The last period of major volcanic activity is stated in the feasibility report as taking place more than 25,000 years ago.

There is little that can be done to mitigate the hazard represented by lava flows or nuee ardantes (hot ash flows) which are known to have occurred during past eruptive periods on Dominica. Only the impact of airborne volcanic ash can be considered in limiting vulnerability from volcanic hazard. The effects of ash include short-circuiting exposed high tension wires, abrading turbine blades, and damaging internal combustion engines. Ash blowing into switchyards, even some distance from the eruptive center, would be capable of causing arcing between high tension cables. In addition to the obvious problems caused by this arcing, it can also start fires in the immediate area. Ash falling on water in open tanks or in reservoirs will be carried through most grit removal Systems. The siliceous composition of this material makes it very abrasive despite its small particle size. This fine dust also poses a threat to internal combustion engines ranging from vehicles to stationary emergency generators. Normal air cleaner systems quickly become ineffective leading to clogging and internal abrasion which render the engines inoperable.

REDUCING VULNERABILITY

It is possible to reduce the vulnerability of facilities in a number of ways. The most cost effective way is to reduce vulnerability to natural hazards prior to construction by conducting pre-construction investigation, selecting appropriate design criteria, and incorporating this criteria in the final design and construction. This approach ensures the full costs and trade-offs to different feasible alternatives are displayed prior to deciding on the final form of the project. It is possible to retrofit or make structures less vulnerable to natural hazards after their construction. However, this is inevitably more expensive and can be less effective in reducing vulnerability than efforts done prior to construction.

Design criteria must reflect the best available information. The search for applicable information regarding natural hazards in the project area must be thorough and take advantage of all information known by the project proponent and other entities involved in planning and development as well as those responsible for natural hazard study and mitigation. The pre-construction studies should ensure that all appropriate disciplines are employed in developing the design criteria. For example, sufficient expertise to fully develop slope stability criteria for constructed embankments and foundations must be complimented by engineering 8eologic studies of natural slope stability important to project components. When sufficient data upon which to base design criteria are lacking in the project area, use of surrogate data or well-tested models are appropriate means for developing design criteria. For example, the use of flood flow data from Martinique as a surrogate for flood data unavailable on Dominica. An important aspect of this means for developing design criteria is the stating of all critical assumptions in using surrogate data or models.

For existing facilities, retrofitting and maintenance are the only means for reducing vulnerability to natural hazards. Retrofitting means changing the existing facility in some way which changes its vulnerability to a natural hazard. This may take the form of adding to the existing facility. For example, buildings can have additional beams or other strengthening elements added to increase survivability during seismic ground shaking. Another example would be the addition of tie-down to roofs to reduce vulnerability to wind.

Maintenance is the other means for reducing vulnerability to natural hazards. It provides fewer opportunities for reducing vulnerability and often amounts to limiting the adverse impact of a natural hazard. Appendix B describes some of the recommended maintenance for the Dominica Hydroelectric Expansion Project. Maintenance measures for reducing natural hazard effects could be incorporated into this type of program. For example, the vulnerability of sediment damage to turbine blades from landslide activity or ashfall during a volcanic eruption could be limited to increasing the frequency of maintenance of grit tanks on pipeline intakes to ensure their maximum effectiveness.

DISCUSSION

It should be clear from the proceeding sections that hydroelectric facilities can be vulnerable to a number of natural hazards. The variety of components comprising a hydroelectric project complicates addressing reduction of this vulnerability. Buildings such as powerhouses are more commonly addressed in established codes for avoiding the effects of natural hazards. Therefore, appropriate design criteria are more readily determined for these components. Expertise is likely to exist within a local utility company to identify appropriate criteria for natural hazards commonly dealt within the company's local area. Outside expertise would be needed to address natural hazards which might exist within the local area but not be normally addressed for current operations by the local utility company. Less common components such as pipelines, intakes, and switchyards require more analysis to ensure adequate design criteria is developed. Outside expertise should be sought for developing design criteria for these parts of a hydroelectric project.

Whatever the source of design criteria, it is important that qualified specialists should scrutinize the criteria to ensure that all available information was used. The expensive redesign of the pipeline at Trafalgar Cliff was attributed to "...unforeseen geological conditions...". This was more a failure to use all existing information as rockfall and rockslide hazard associated with the bedrock forming Trafalgar Cliff was documented (DeGraff, 1987). Unforeseen conditions will arise in a project but should be truly unforeseen rather than overlooked during project design. Similarly, review should be given to design criteria proposed by consultant which was developed m geographically different environments. This will ensure that their application to the local project area is appropriate and does not violate an underlying assumption which could call the criteria into question. Some natural hazards may require investigation to develop an adequate design criteria. This might take the form of a geotechnical drilling and testing program such as was done for the Dominica Hydroelectric Expansion Project to ensure adequate foundation design criteria for Fresh Water Lake dam and similar structures. While such investigation are an additional expense, the design criteria developed from this data is likely to lead to significant cost savings in the long term life of the project. Finally, it is important to ensure that criteria is developed which addresses all the natural hazards which might exist within the project area. A project which includes flood frequency design criteria for spillways and intakes but fails to recognize that the powerhouse is sited within the 100-year flood plain would be overlooking a critical natural hazard situation.

Like most hazard reduction situations, it is far more cost-effective to avoid or limit natural hazard effects by incorporating this information into the project design. Where the effects of a natural hazard cannot be avoided, this pre-project approach ensures that this consequence is known. Its economic effect will be fully appreciated during the feasibility study and operations can be planned to deal with these consequences when they occur. For an existing project which is experiencing the effects of natural hazard, it is important to regularly evaluate the cost-effectiveness of retrofitting or increased maintenance. Re-building a landslide-damaged pipeline may be cost-effective once at a particular location. But repeated repair coupled with a high likelihood of future landslides may make a more costly re-design or installation of a protective measure more cost-effective. This may be true of maintenance. If turbine blades are being replaced regularly earlier than their design life due to sediment, it may be cost-effective to have more frequent maintenance of intakes and other points where sediment can be removed from the water.

REFERENCES

Anonymous, 1984. Expansion of hydro-electric resources feasibility study. Lavalin International, 105 pgs. (a report prepared December 1984 for the Government of the Commonwealth of Dominica by a Canadian consulting firm).

Anonymous, 1987. Expansion of hvdro-electric resources - design criteria. Lavalin International, 60 pgs. (a report prepared April 1987 for the Government of the Commonwealth of Dominica by a Canadian consulting firm).

Anonymous, (undated). Dominica hvdroelectric expansion project - project completion report. SNC-Lavalin International, 72 pgs. (a report documenting events through Oct. 1992 prepared for the Government of the Commonwealth of Dominica by a Canadian consulting firm).

Aspinall, W.P., Shepard, J.B., Woo, G., Wightman, A, Rowley, K.C. Lynch, L.L., and Ambeh, W.B., 1994. Seismic ground motion hazard assessment at a site near a segmented subduction zone: the Roseau Dam. Saint Lucia West Indies: Earthquake Spectra, vol. 10, No.2, p.259-292.

DeGraff, J.V., 1987. Landslide hazards on Dominica West Indies - Final Report. Organization of American States, Washington, D.C., 25 pgs.

DeGraff, J.V., Bryce, IL, Jibson, ILW., Mora, S., and Rogers, C.T., 1989. Landslides: Their extent and significance in the Caribbean, in Brabb, E.E. and B.L. Harrod (eds.), Landslides: Extent and Economic Significance. A.A. Balkema: Rotterdam, p. 51-80.

Duncan, J.M. and Buchignani, A.L., 1975. An engineering manual for slope stability studies. Department of Civil Engineering, University of California, Berkeley, CA, 47 pgs.

Walsh, ILP.D., 1985. The influence of climate, lithology, and time on drainage density and relief development in the volcanic terrain of the Windward Islands in I. Douglas and t. Spencer (eds.), Environmental Change and Tropical Geomorphology. p.93-122, London: Allen & Unwin.

FIGURES

Figure 1. Topographic map of the Cominica Hydroelectric Expansion Area with physical features and project components.

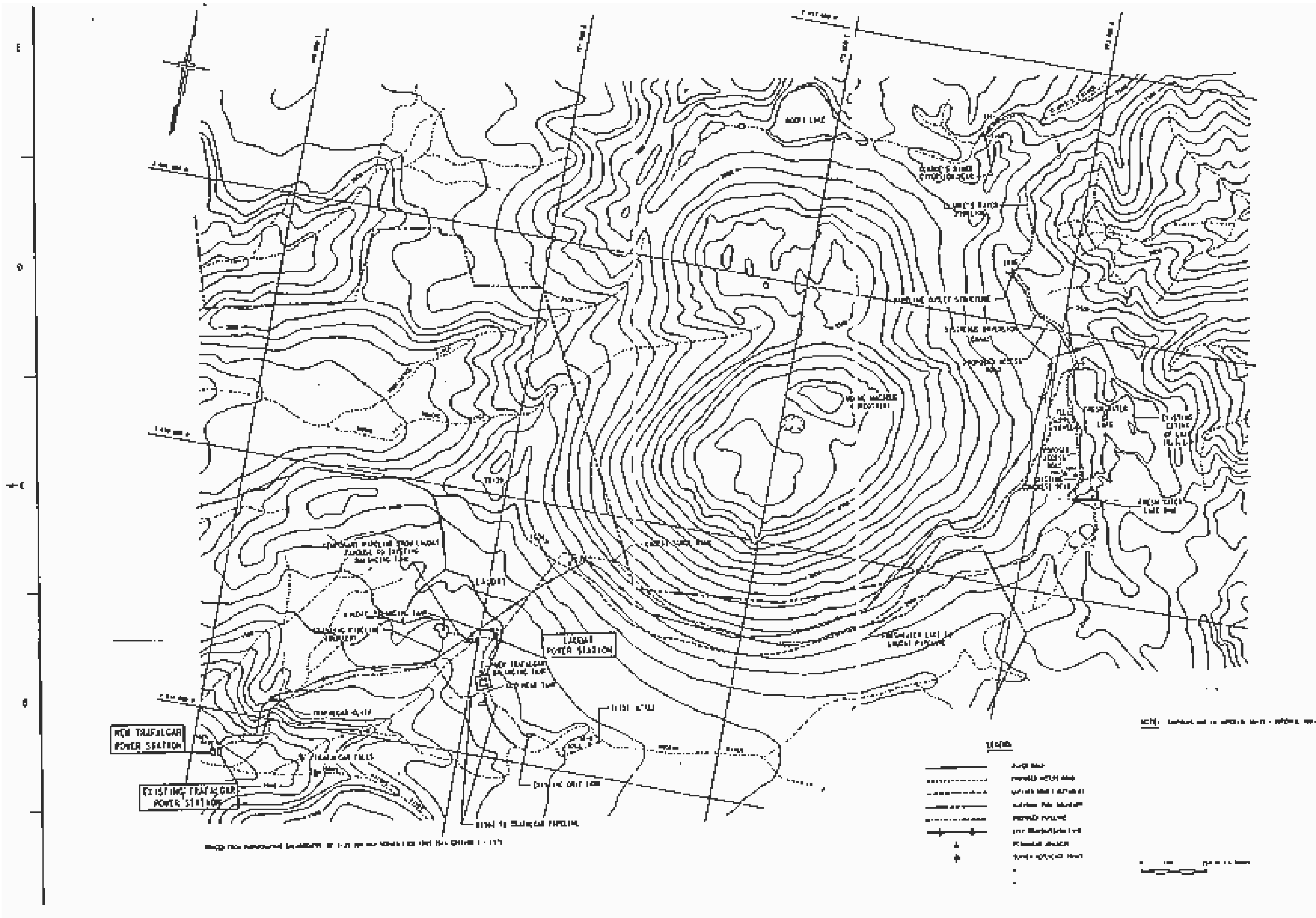


Figure 2. View of the rockfill dam forming Fresh Water Lake in 1994.

Figure 3. Low pressure woodstave pipeline from Fresh Water Lake to the Laudat surge tank. This section was re-designed to incorporate a Bailey bridge to restore the foundation pad destroyed by the Morne Macaque landslide in 1989.

Figure 4. High pressure pipeline conducting water from the Laudat surge tank (on slope in background) and the powerhouse at Laudat.

Figure 5. View of Laudat powerhouse. The tailrace is visible to the right side of the building.

Figure 6. View of the Titot intake structure and woodstave pipeline which conducts water to New Trafalgar Balancing Tank. Titot Gorge is located immediately upstream from the location.

Figure 7. View of Trafalgar Cliff. The high pressure pipeline is visible in the background and leads to the intake structure in the foreground.

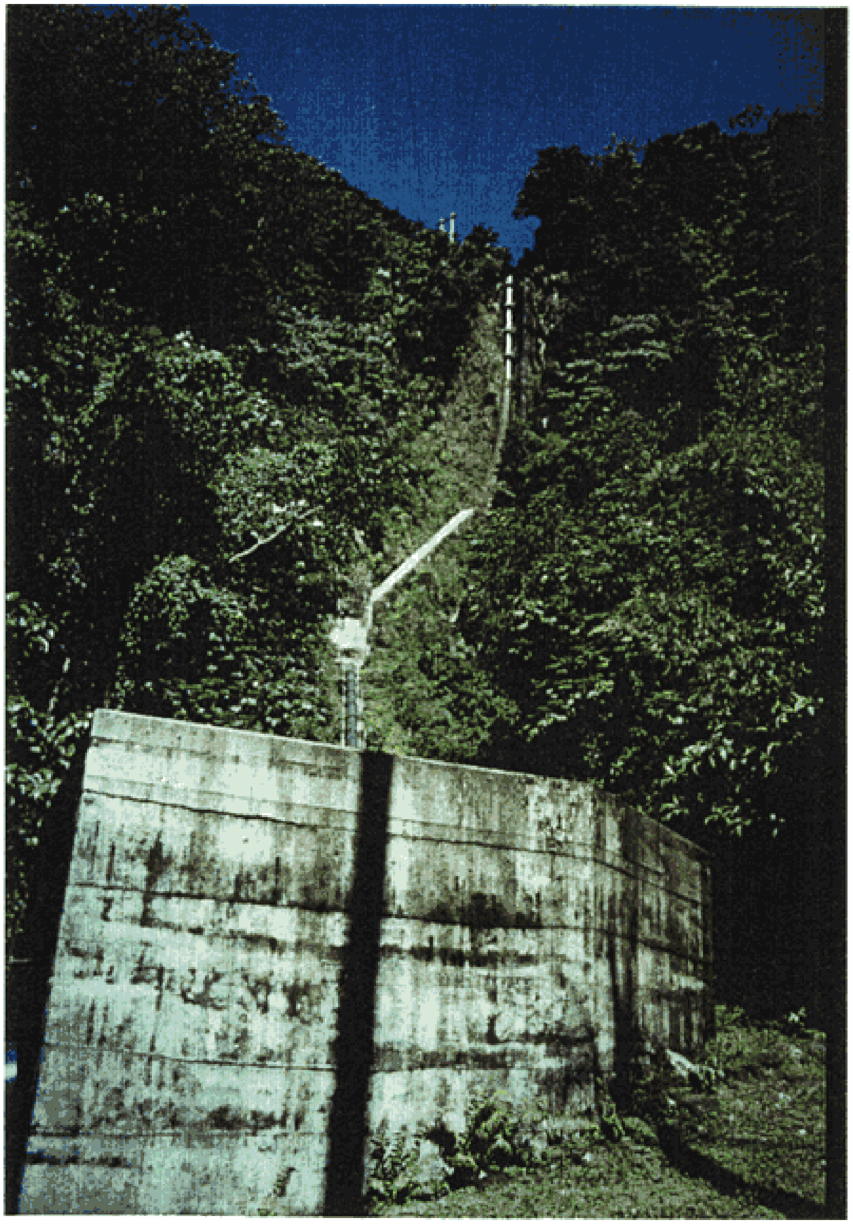


Figure 8. View of the New Trafalgar powerhouse.

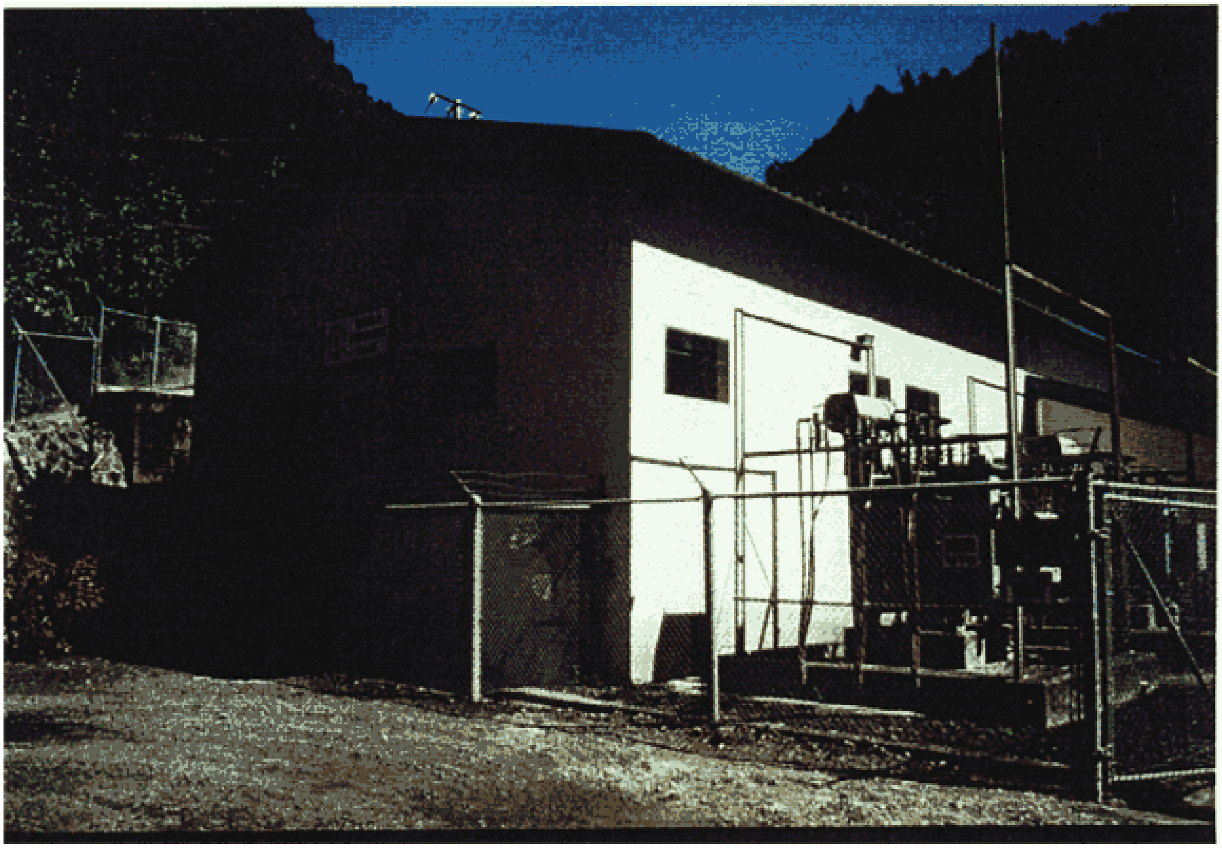


Figure 9. The switchyard facilities at the New Trafalgar powerhouse.

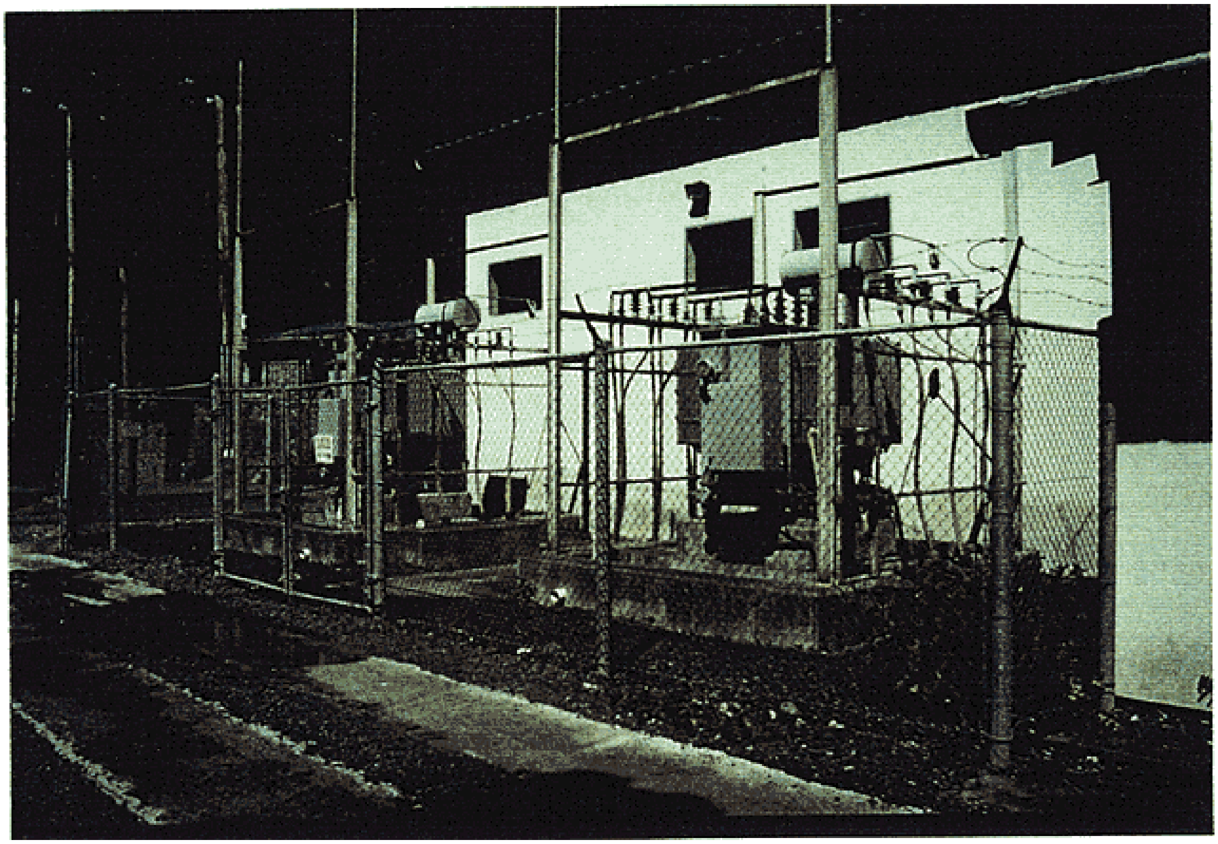


Figure 10. Project area map with the location of problem areas encountered during hte following construction period. The lightly shaded areas represent areas mapped by DeGraff (1987) as high landslide hazard. Unshaded areas are mapped as moderate landslide hazard.

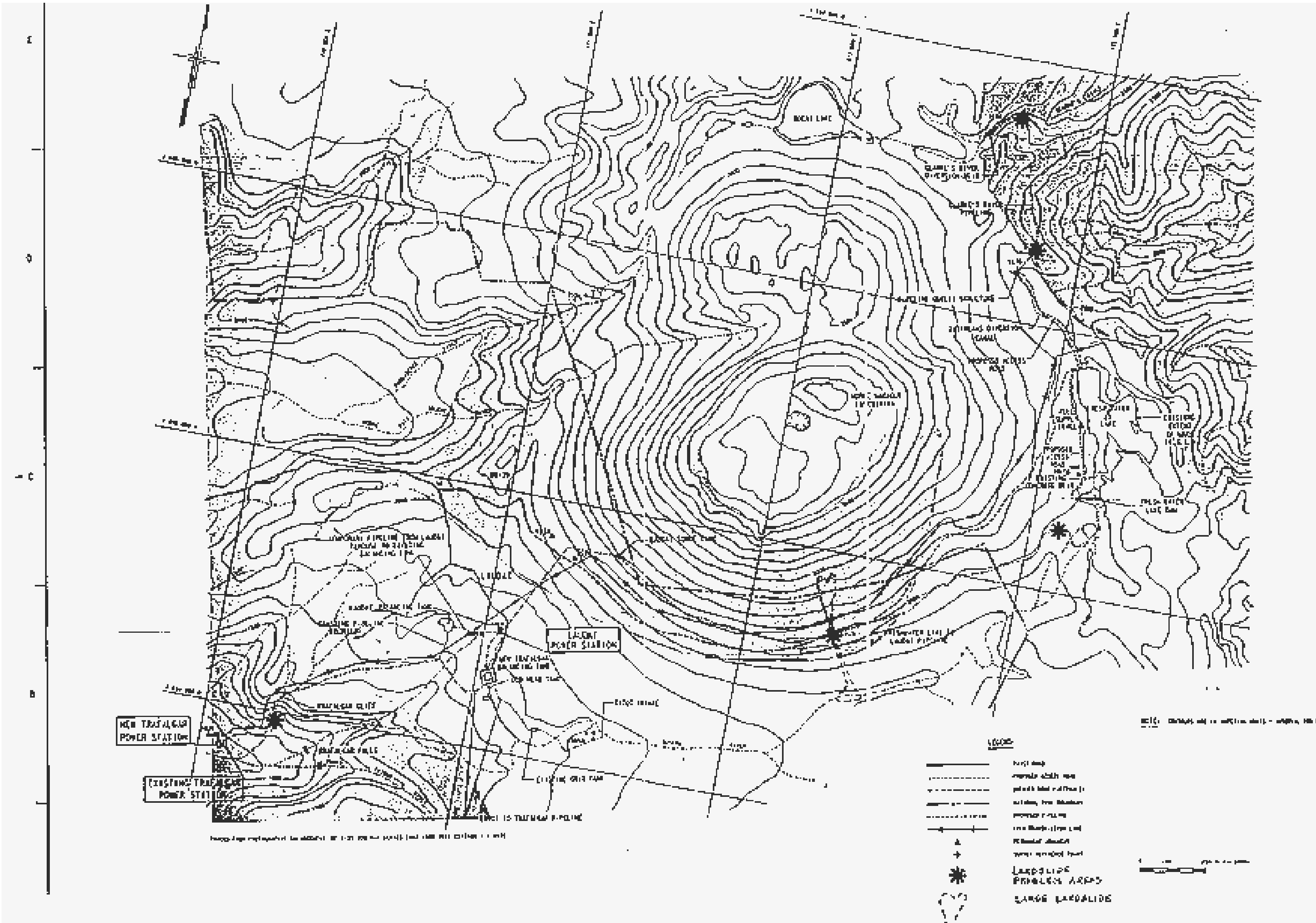


Figure 11. View upslope of the large landlslide on the slopes of Morne Macaque which ocured in 1989. The view is taken from the Bailey bridge installed to convey the woodstave pipeline from Fresh Water Lake across the slide-created gorge. The upper part of the landslide is between 2,500 adn 3,000 feet upslope from this view point.

Figure 12. View downslope from the Bailey bridge showing the path of the large landslide downslope and the landslide deposit of rack and soil in the Roseau River valley bottom. The deposit is located supstream of Titot Gorge and generated sediments affecting the Titot Gorge intake.

Figure 13. Closer view of Trafalgar Cliff showing the steel support and concrete encasement design necessitated by rckfall instability. The bedrock at this location is recognized in landslide hazard mapping (DeGraff, 1987) as associated with rockfalls and rockslides in nearby river valleys.

Figure 14. View of the landslide which damaged the woodstave pipeline near the Clarke's river diversion. The diversion structure is just beyond and to the right of this view. Slide material ranged from soil particles to the boulders such as the one visible in the forground.

Figure 15. View of the section of the woodstave pipeline from Clarke's river diversion which was affeted by landslides in 1992 and 1993. A reparied break in the pipeline is seen at the far end.

Figure 16. A close up view of the repaired break in the Clarke's river diversion woodstave pipeline. This is the section visible in Figure 15.

APPENDIX A: DESCRIPTION OF PROJECT COMPONENTS FOR THE DOMINICA HYDROELECTRIC EXANSION PROJECT

2.0 PROJECT DESIGN DATA

2.1 INTRODUCTION

The basic Design Criteria are contained in a report entitled Expansion of Hydro electric resources, Design Criteria, prepared by Lavalin International Inc. for the Government of the Commonwealth of Dominica and dated April 1987. The following paragraphs extract the parameters for each of the project Structures updated to reflect the as-built status where necessary. Reference is made to the relevant as-built drawings, the originals of which have been handed over to Domlec. Selected drawings have been included in this report in Appendix E together with a complete list including manufacturer's drawings in Appendix C.

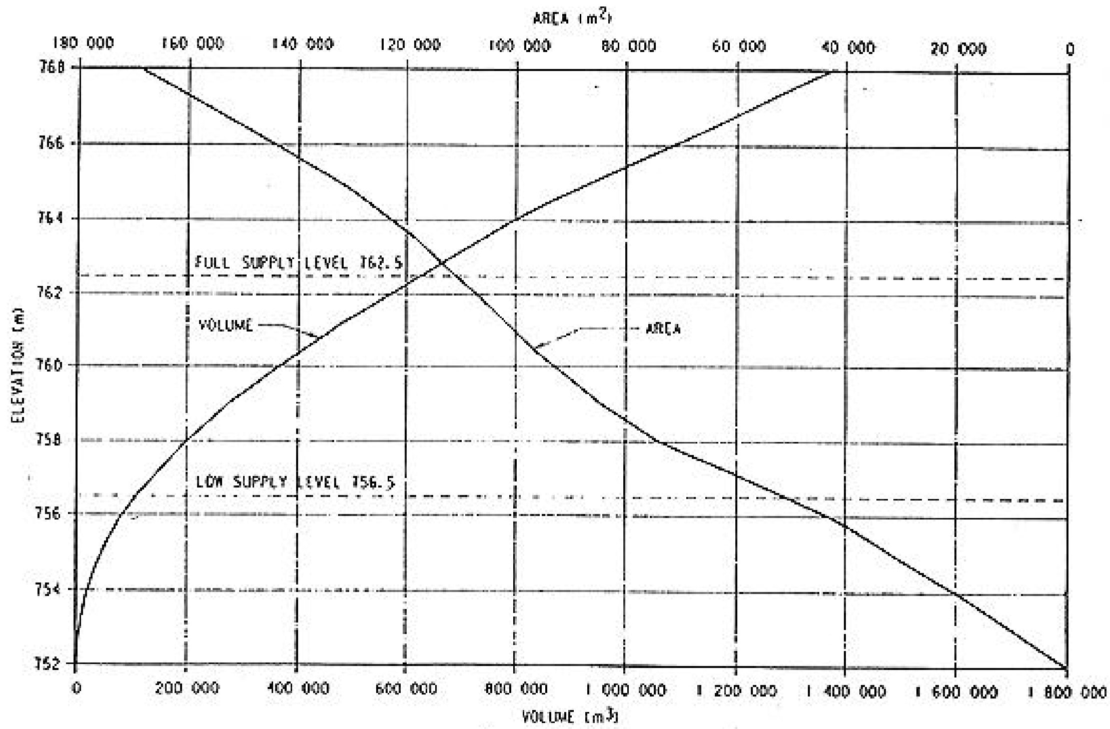
2.2 PRINCIPAL PROJECT PARAMETERS

2.2.1 Clarke's River Diversion - Drawing E-1003)

Diversion Weir Type	
Type	Mass concrete free overflow weir with reinforced concrete wing walls and concrete filled cutoff trenches at the heel and toe.
Crest Elevation	800.0m
Crest Width	0.6m
Crest length	8.0m
Upstream Slope	1 H: 1V
Downstream Slope	1H: 1V
Height above river bed	2.5m
Design flood	30.2 m3/s
Flood waterlevel	801.64m
Intake	
Type	Reinforced concrete drop box with trash screen
Crest Elevation	799.60 m
Crest length	1.4m
Design flow	0.32m3/s
Pipeline	
Material	Woodstave
Diameter	450 mm
Length	988 m

2.2.2 Fresh Water Lake Reservoir - (Drawing E-l0l4/16/63)

Dam	
Type	Rockfill dam with an upstream PVC membrane.
Crest Elevation	765.0m
Full supply level	762.5m
Minimum Operating Level	756.5m
Approx. height above river bed	10.0m
Upstream Slope	3 H: 1 V
Downstream Slope	3 H: 1 V
Crest Width	5.0m
Spillway	
Type	Concrete overflow discharging into a concrete lined chute 18.00 m long and a gabion lined discharge channel 105 m long.
Crest Elevation	762.5m
Design Capacity	15.9m3/s (1 in 1000 year flood)
Spillway Surcharge	1.22 m (10.79 m3/s i.e. 1 in 100 year flood) 1.58 m (in 1000 year flood)
Width of oerflow section and chute	4m
Width of discharge channel	Varies from 4 m to 20 m at bottom
Intake & Low Level Release	
Type	Bottom outlet discharging into precast concrete pipe constructed through the dam.
Invert Elevation	753.5 m
Design flow	0.71 m3/s



AREA - VOLUME CURVE

2.2.3 Titot Intake (Drawing E-l040)

Type	Free overflow weir constructed of concrete. Intake comprises a 3 m wide by 21.6 m long sediment tank with a box type inlet with inclined trash rack.
Crest Elevation of Weir	544.514m
Height Above Riverbed	0.5m
Crest length	17.05m
Spillway design flow	29.9m3/s
Desander weir crest level	543.77m
Intake design flow	1.09m3/s
Normal Operating Level	544.11m
Invert Level of pipe	542.0m

2.2.4 Balancing Tank (Drawing E-1035)

2.2.4 Balancing Tank (Drawing E-1035)

Type of Structure	PVC lined excavation with concrete overflow spillway.
Bottom Dimensions	25m x 25m
Height	5m
Excavated Slopes	3 H: 1 V
Fill Slopes	2 H: 1 V
Spillway Design Capacity	1.33 m3/s
Spillway crest level	544.12m
Normal operating level	543.50m
Minimum operating level	541.00m
Active Tank Volume	4000m3

2.2.5 Power Facilities

a) Laudat - (Drawing E-1030)

Low Pressure Pipeline

Type: Woodstave
Diameter (I.D.): 914 mm
Length: 2267 m

Surge Tank

Type: Woodstave
Diameter (I.D.): 4.0m
Height: 16.7m

High Pressure Pipeline

Type: Steel
Diameter: 743 mm (I.D.), 760 mm (O.D.)
Length: 652m

Powerhouse at Laudat

Gross Head: 217.5m
Design Flow: 0.17m3/s
No. of units: 1

b) Trafalgar Expansion - (Drawing E-1055)

Low Pressure Pipeline

(From Titot Intake to New Trafalgar Balancing Tank)

Type: Woodstave
Diameter: 1016mm

Length: 534m

(From Laudat Tailrace to New Trafalgar Balancing Tank)

Type: Woodstave
Diameter: 760 mm
Length: 163 m

(From New Trafalgar Balancing Tank to Trafalgar Cliff)

Type: Woodstave
Diameter: 1016 mm
Length: 533 m

High Pressure Pipeline

Type: Steel
Diameter: Above cliff - 987 I.D. (1016 O.D.); Cliff - 895 I.D. (914 O.D.); Base of cliff to bifurcation to existing powerhouse 895 I.D. (914 O.D.).
Length: Above cliff 330 m; Cliff - 154 m; Base of cliff to bifurcation to existing powerhouse 254 m.

Powerhouse

Gross head: 284.3 m
Design Flow: 1.39 m3Is
No. of Units: 2

APPENDIX B: RECOMMENDED MAINTENANCE PROCEDURES FOR THE DOMINICA HYDROELECTRIC EXPANSION PROJECT

2.3 RECOMMENDED MAINTENANCE PROCEDURES

2.3.1 Civil Works

The following is a list of recommended maintenance for the Civil Works on both the Laudat and New Trafalgar schemes:-

STRUCTURE	RECOMMENDED ACTION
Clarke's River Weir:	
Trash Racks	Routine inspection to ensure no blockage. Racks should be kept free of debris.
Catch Pit	Routine inspection of basin to ensure no build-up of sediment in bottom. Flush pit through sluice pipe as required.
Slide Gates	Grease hoist stems as required for proper operation.
Clarke's River Pipeline:	
Pipes	Routine inspection/maintenance of woodstave and steel pipes including pipeline right-of-way and drainage ditches.
Dissipation Basin	Remove any sediment/debris which may build-up in bottom.
Three Streams Canal:	
Open Channel	Routine removal of vegetation growth in flow path to ensure free flow of water.
F.W.L. Dam:	
Slide Gates	Grease hoist stems as required for proper operation.
B/fly Valve Pit	Regular inspection to ensure no build-up of water in basin. Basin should be kept as dry as possible to prevent damage to butterfly valve motor.
Intake Trash Racks	Inspect racks and basin area when lake is at L.S.L. Any debris should be removed.
Box Culvert	Routine measurement of flow through V-notch weir to monitor seepage. Dewater annually to inspect & maintain woodstave pipe.
F.W.L. - Surgetank Pipeline:	
Pipes	Routine inspection/maintenance of woodstave and CANRON pipes including pipeline right-of-way and drainage ditches.
Modular Bridge	Monitor slide area for build-up of material upstream of bridge.
Surge Tank	Routine inspection/maintenance of structure.
Steel Pipeline:	
Pipes	Routine inspection of pipe joints for possible leakage. Maintain steel pipes and structures as required.
Laudat Intake:	
Sediment Tank	Routine inspection of basin to ensure no build-up of sediment in bottom. Flush pit through sluice pipe as required.

Slide Gate	Grease hoist stems as required for proper operation.
Trash Racks	Routine inspection to ensure no blockage. Racks should be kept free of debris.
Laudat Stream Diversion:	
Inlet & PVC Pipe	Routine inspection of inlet to clear any debris and pulling of pipe to remove all algae growth.
Pipeline No.6:	
Pipes	Routine inspection/maintenance of woodstave pipe including pipeline right-of-way and drainage ditches.
Titot Intake:	
Sediment Tank	Routine inspection of basin to ensure no build-up of sediment in bottom. Flush pit through sluice pipe as required. Flush frequently during periods of heavy rainfall.
Slide Gate	Grease hoist stems as required for proper operation.
Trash Racks	Routine inspection to ensure no blockage. Racks should be kept free of debris.
Intake Channel	Routine inspection for build-up of debris in upstream channel. Remove material as required.
Pipeline No.7:	
Pipes	Routine inspection/maintenance of woodstave & steel pipes including pipeline right-of-way and drainage ditches.
Balancing Tank:	
Slide Gate	Grease hoist stems as required for proper operation.
Trash Racks	Routine inspection to ensure no blockage. Racks should be kept free of debris.
Pipeline No. 8	
Pipes	Routine inspection/maintenance of woodstave & steel pipes including pipeline right-of-way and drainage ditches.
Pipeline No. 9	
Pipes	Routine inspection of pipe joints for possible leakage. Maintain steel pipes, right-of-way (including drainage ditches) and structures as required.
Pipeline No.10:	
Station 27, Top of cliff	Routine inspection of diversion works and removal of debris from overflow pipe intake area and pipe at Stn 26.
Hoist	Routine maintenance of hoist winch and accessories.
Cliff	Monthly inspection of pipe joints, platforms, concrete encasement and rock anchors & witnesses. Maintain as required.
Pipelines No. 11-14:	
Pipes	Routine inspection of pipe joints for possible leakage. Maintain steel pipes, right-of-way (including drainage ditches) and structures as required.
Padu Control Tank:	
Slide Gate	Grease hoist stems as required for proper operation.
Trash Racks	Routine inspection to ensure no blockage. Racks should be kept free of debris.